JPL

Piezoelectric actuated drills developed at JPL and the Percussive Augmenter of Rotary Drills (PARoD)

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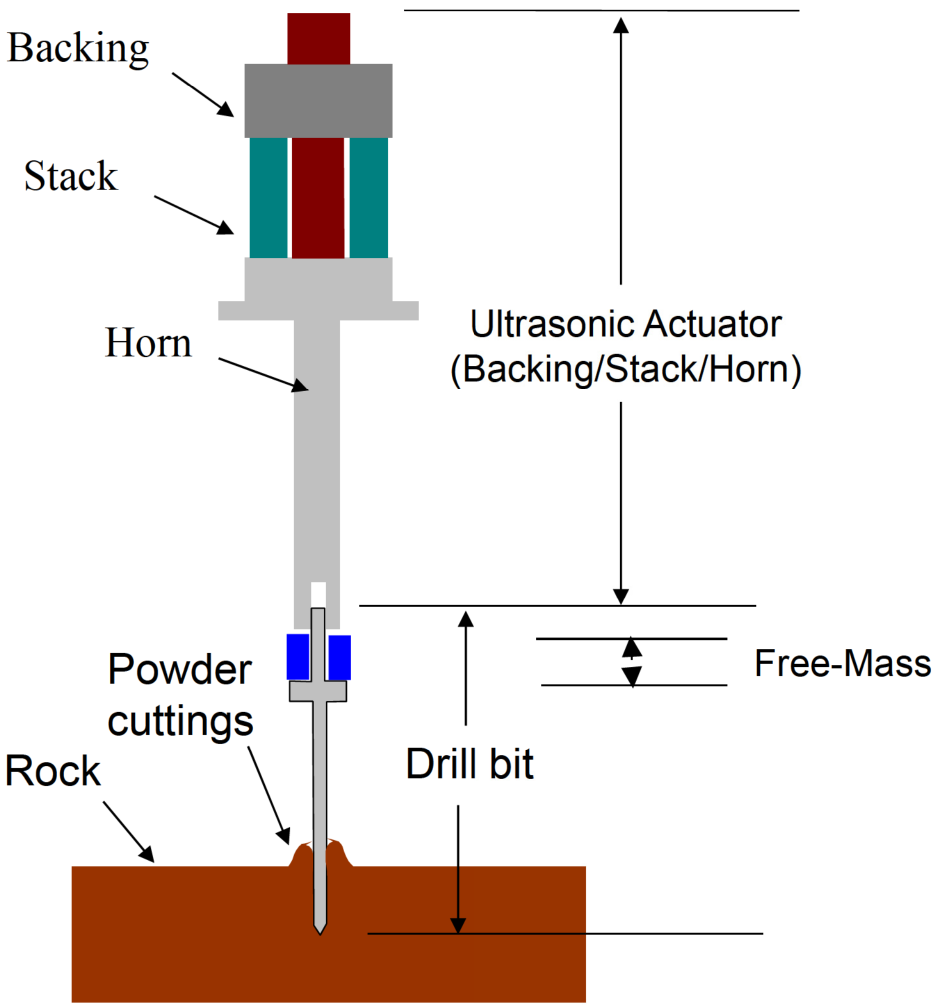
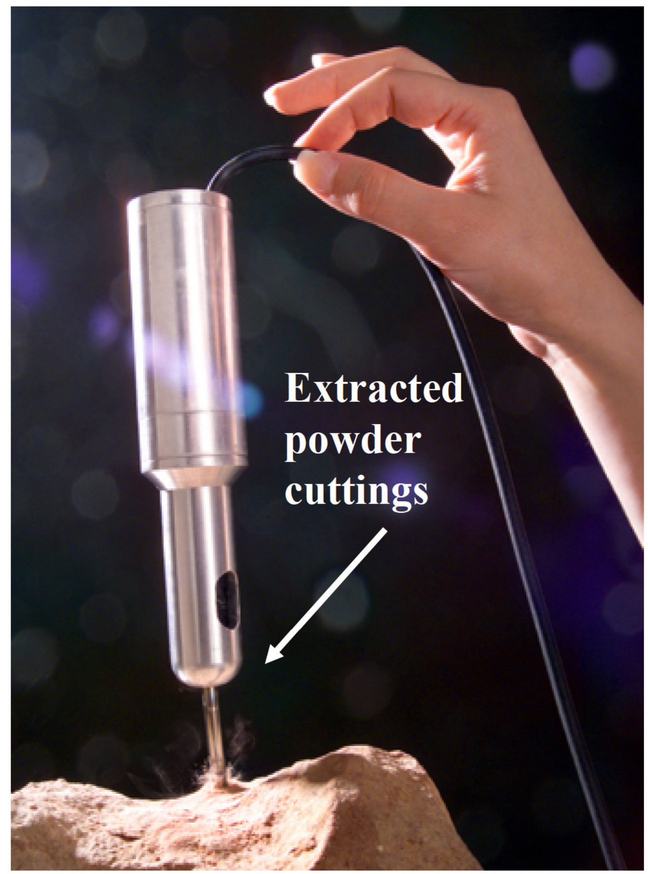
Presentation to Schlumberger and Placidus,

June 28, 2012

Ultrasonic/Sonic Driller/Corer (USDC)



2000 R&D 100 award



Comparison between the USDC and conventional Drills

	Conventional Rotary Drills	USDC
Axial preload	>100N (typically 150N)	<10N
Drill walk at core initiation	>30N·m induced torques and >100N tangential forces	<1N
Average power to create 10-mm core	>20-30 W. Can be reduced but the drilling efficiency goes down.	Can be as low as 2-3W (lower power requires longer drilling)
Duty cycling	Involve staggering loss of efficiency	Very little efficiency loss (2W average at 25W peak was demonstrated)
Current Overshoot	3-4 times larger startup electrical currents than those during continuous operations	<20% even with duty cycling.
Drill chatter	Induces low frequency (2-10Hz) and high force perturbations on the drilling platform	Minimal
Support system	Requires stable and massive platforms with solid anchoring	Minimal
Drilling/Coring soft rock	Shearing and spalling	Compression failure
Drilling/Coring hard rocks	Grinding with corresponding 300% increase in energy consumed per unit volume of removed rock. Require frequent sharpening or replacement. Otherwise, 10 fold increase in heat generation and similar drop in efficiency.	•Spalling •No need for drill bit sharpening

Y. Bar-Cohen and K. Zacny (Eds.), "Drilling and Excavation" Wiley – VCH, Hoboken, NJ, (2009)

List of chapters

1 Introduction
2 Principles of Drilling and Excavation
3 Ground Drilling and Excavation
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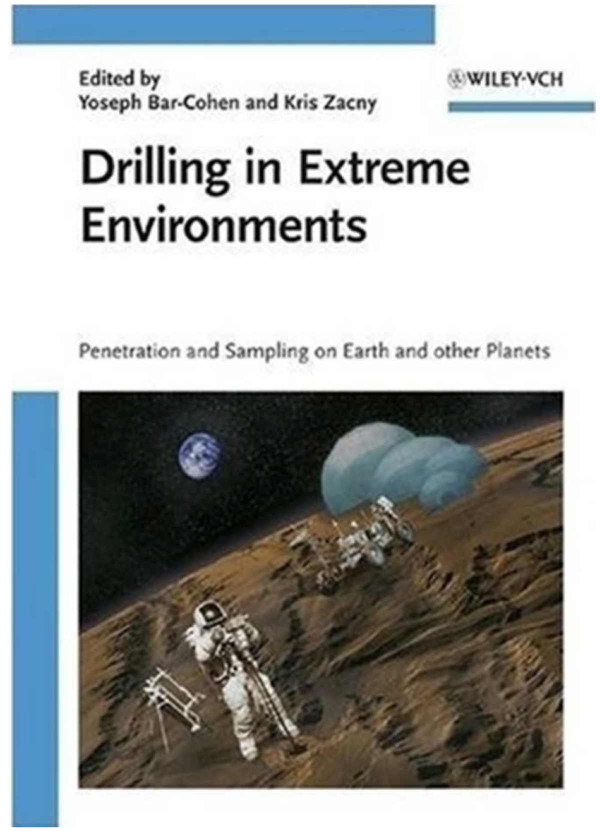
5 Underwater Drilling
6 Extraterrestrial Drilling and Excavation
7 Planetary Sample Acquisition, Handling and Processing
8 Instruments for In-Situ Sample Analysis
9 Contamination and Planetary Protection
10 Conclusions

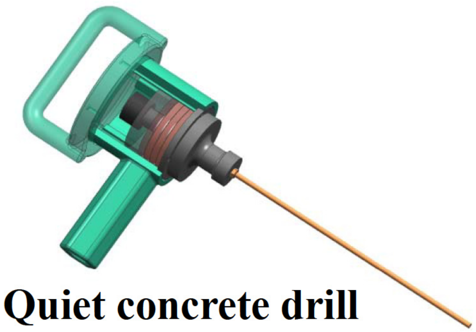


Y. Bar-Cohen and K. Zacny, "Drilling in Extreme Environments - Penetration and Sampling on Earth and Other Planets," Wiley – VCH, Hoboken, NJ, ISBN-10: 3527408525, ISBN-13: 9783527408528, (July 2009) 827 pages

Development of the USDC for various applications

- Drilling/coring complex media and novel applications
  - Rotary/hammer using separate actuators (U/S and motor) as well as a single piezo-stack
  - Large scale drills: Ultrasonic/sonic gopher for deep coring of ice; Auto-Gopher; and U/S jackhammer
  - U/S anchor
  - Packed soil penetrator
- Novel piezo-actuators
  - Flextensional hammer
- Novel free-mass designs
- Enhanced USDC using novel horns
  - Dog-bone shape horn
  - Folded horn
- Novel bits
  - Ultrasonic/Sonic Rock Abrasion Tool (URAT)
  - Interchangeable bit
  - All-in-one bit
- Lab-on-a-drill
  - Sounding source
  - Sampler of cores and powdered cuttings
  - Integrated with a sensor suite
- Operation in extreme temperature environments
  - Low temperatures (down to -200°C as on Titan and Europa)
  - High temperatures (up to +460°C as on Venus)

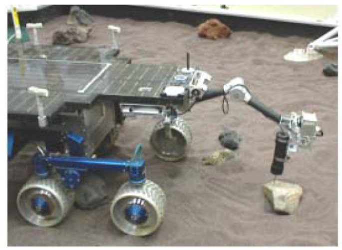
Applications of the USDC

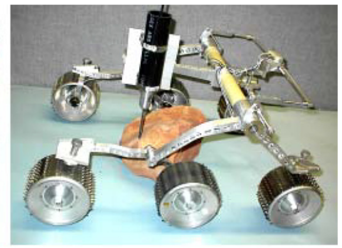


Quiet concrete drill

Powdered cuttings sampler

2000 R&D 100 award

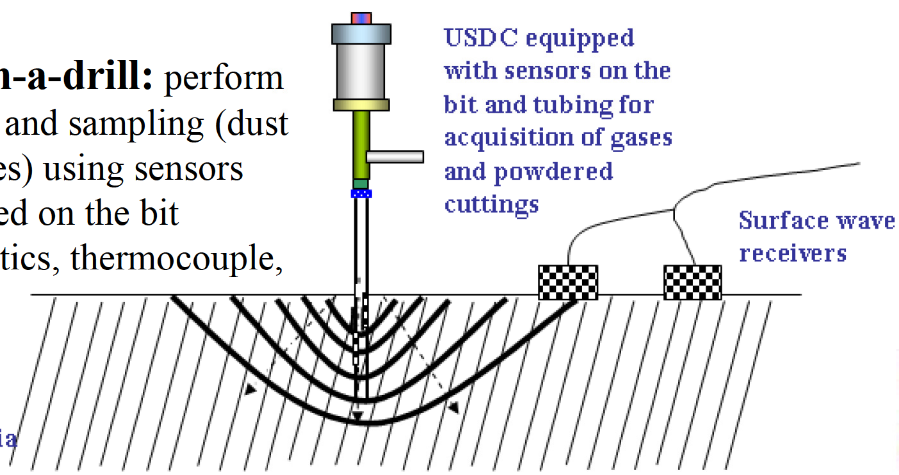




Simple feasibility tests was made operating the USDC from the Sojourner rover platform and the FIDO robotic arm

U-S Gopher for deep drilling

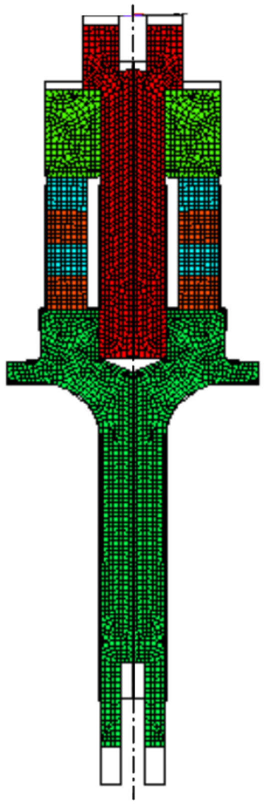
Lab-on-a-drill: perform probing and sampling (dust and cores) using sensors integrated on the bit (fiberoptics, thermocouple, etc.)

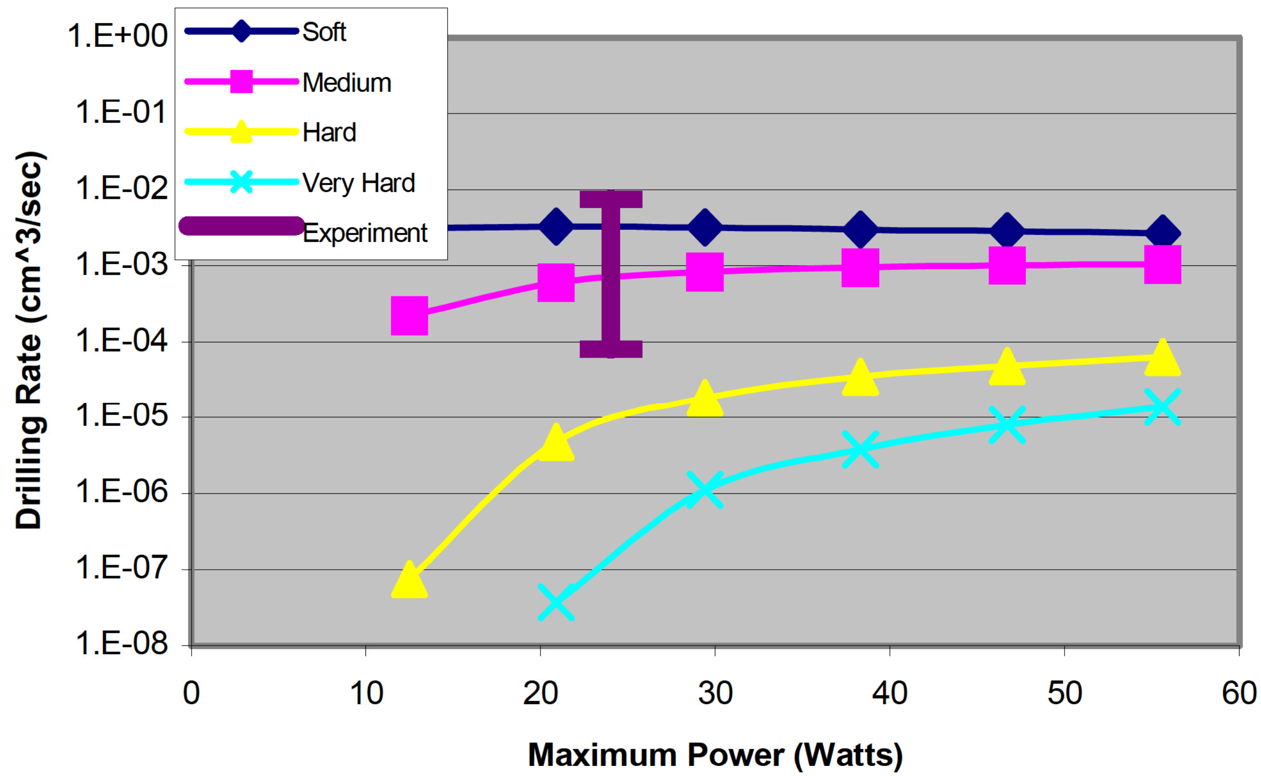


Proto-flight unit

Ultrasonic Rock Abrasion Tool (**URAT**)

Drilling rate for different maximum power

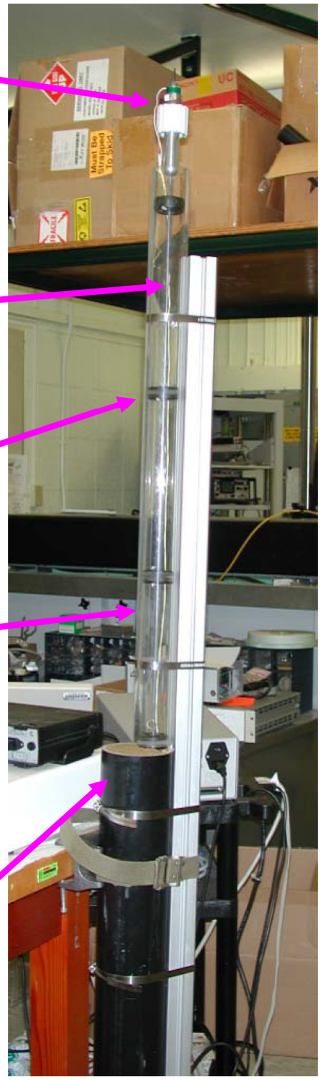




The average power is maintained at 10 watts by duty cycling the power supply

Note: The range described by the error bar was determined experimentally from a variety of rock samples.

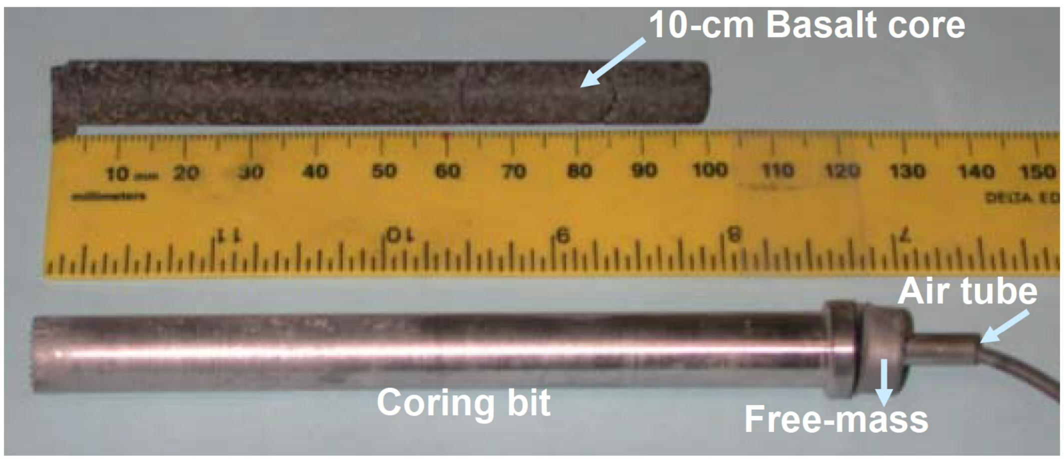
Soil penetrator and testbed



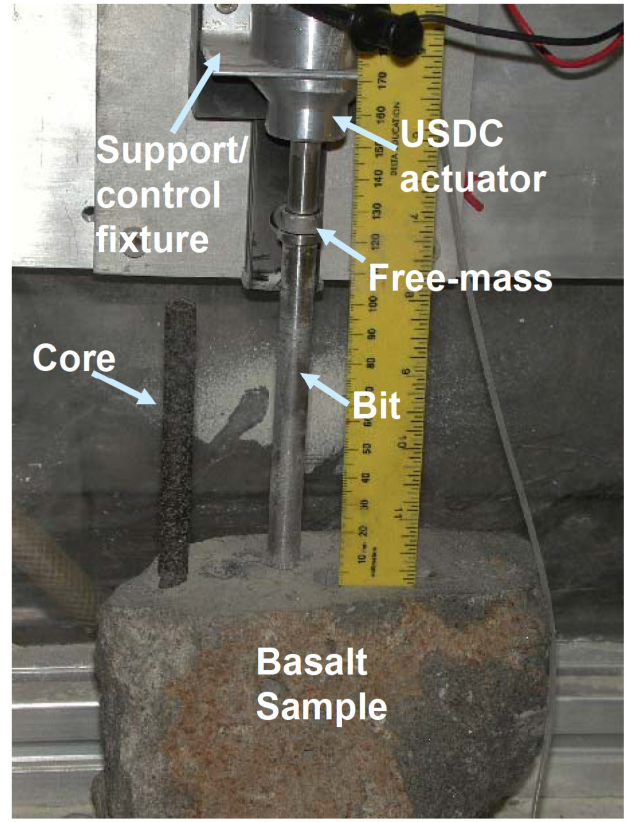
- Using 7 lb preload at ~70W and 20% duty cycled power, we reached a depth of 3-ft (~90-cm) in 30-40min.
- Since we used duty cycling the net drilling time is only about 6-8 minutes.

Coring basalt via the USDC

Using air the power was removed from the hole and allowed to create 10 cm long basalt core

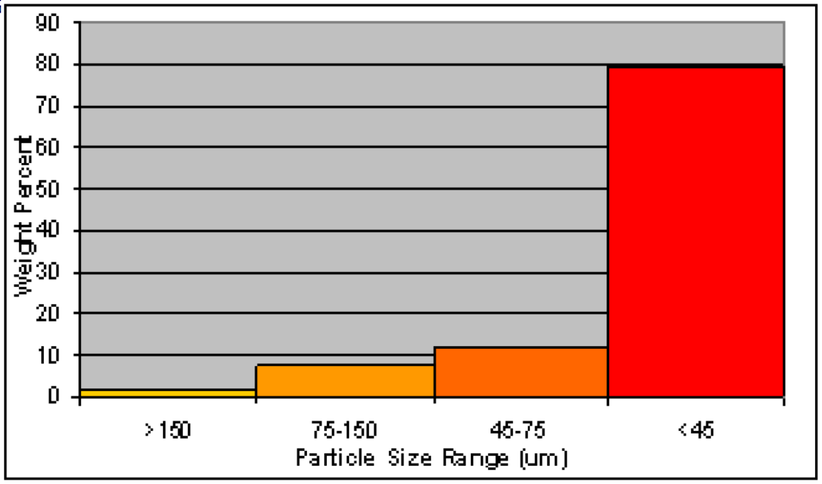


Close-up

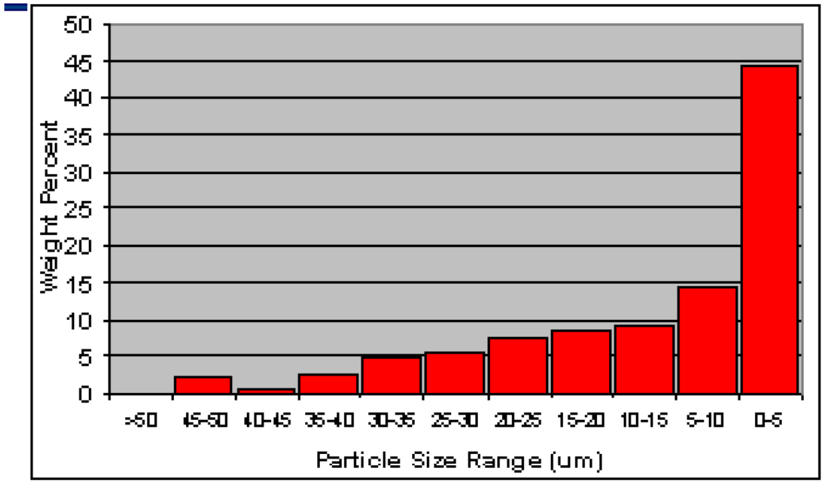


Coring set-up

Chinle Sandstone powder samples made by the USDC



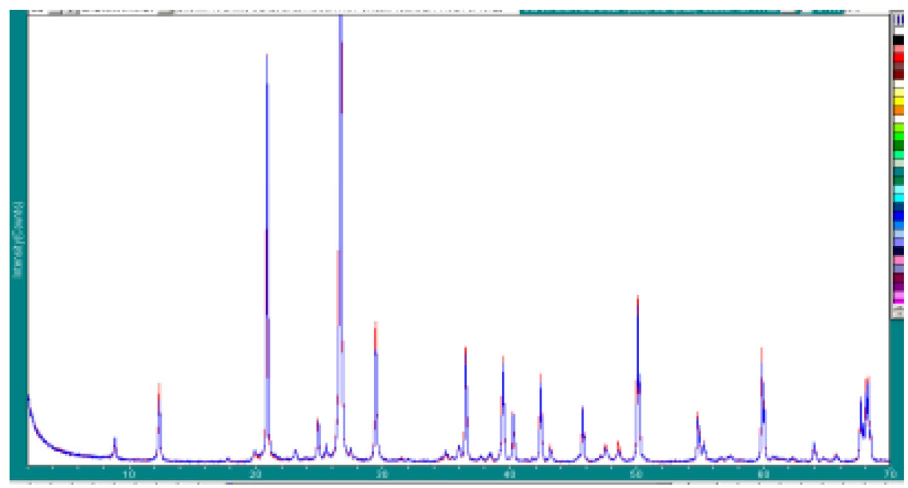
Size fractions obtained during wet sieving



Particle size distribution of the <45μm powder obtained using a Horiba CAPA-500 particle size distribution analyzer.

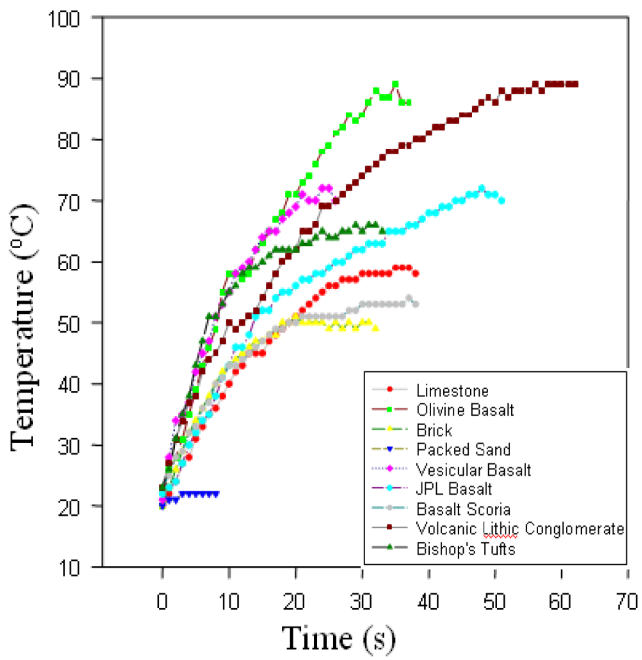
LANL's Lab XRD patterns of the <45 μ m USDC powder (blue) compared to the Retsch milled <5 μ m powder (red).

Note: The patterns compared very well.



Bit temperature measurements

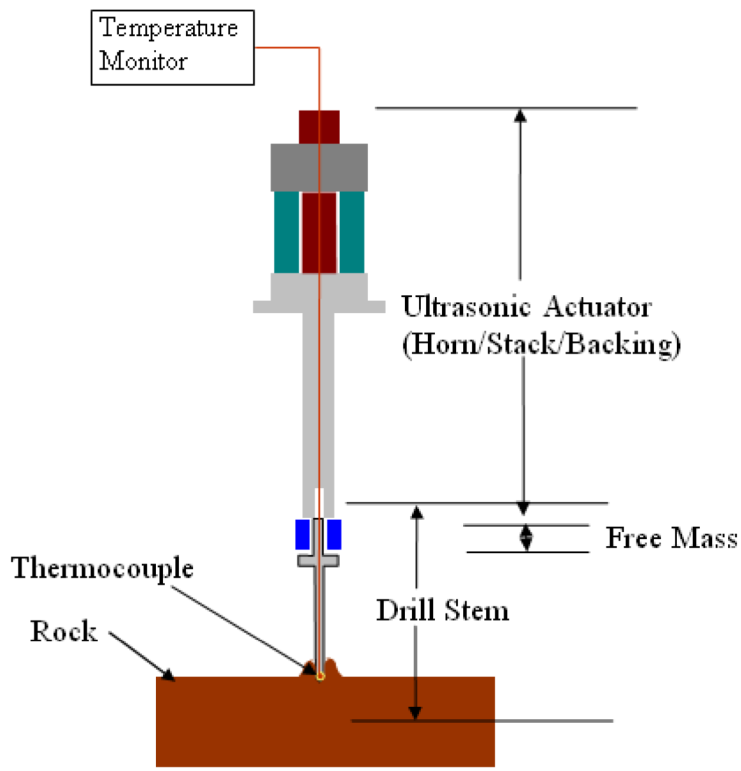
A thermocouple was integrated into the USDC bit to allow real time monitoring the temperature during drilling.



Temperature rate of rise and maxima as a function of time for drilling variety of media

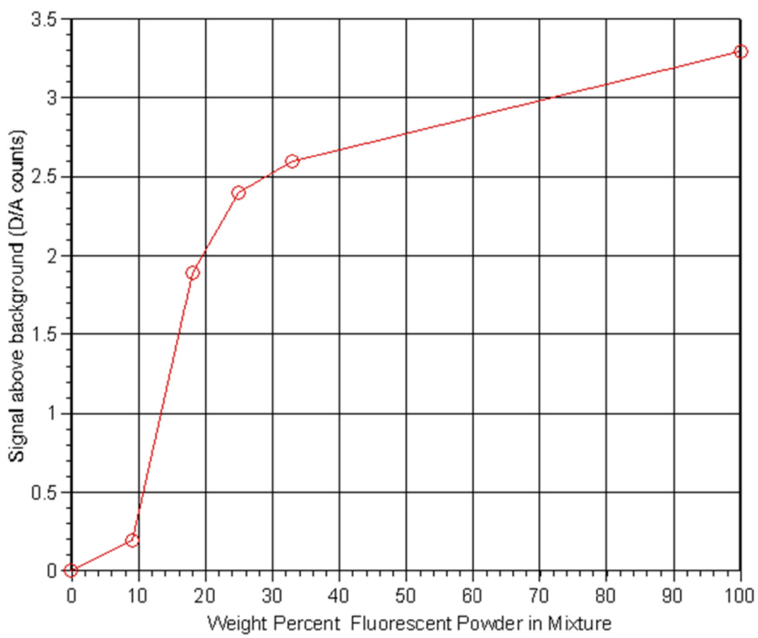
Power < 40 watts

Bit diameter = 3.6 mm

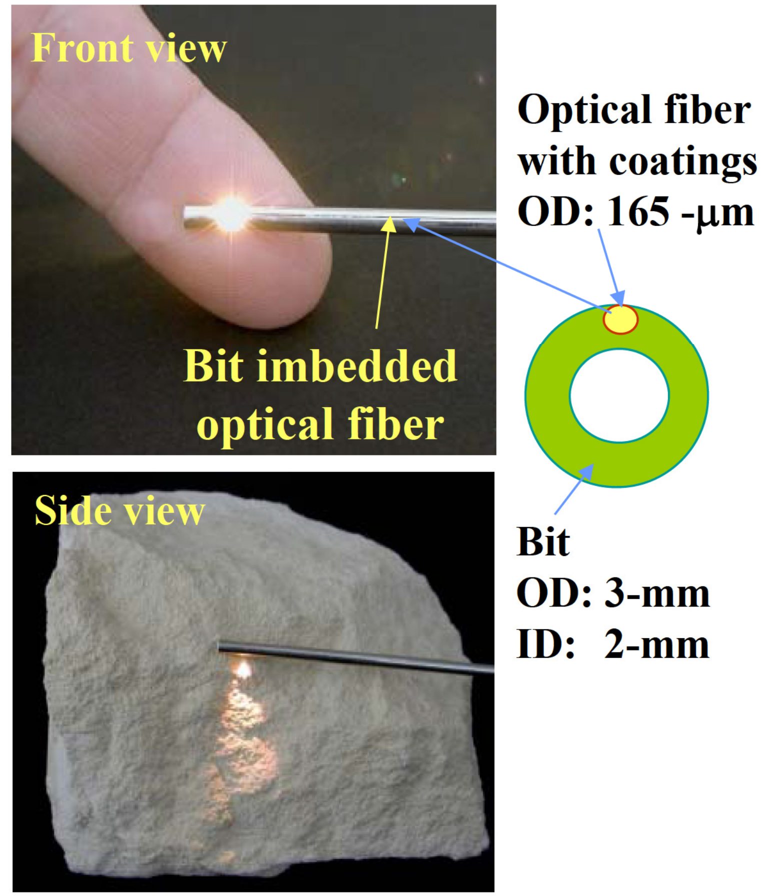


Experimental Setup

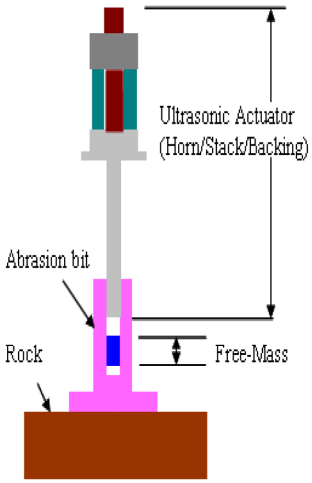
Integrated fiberoptics and measured reflectivity



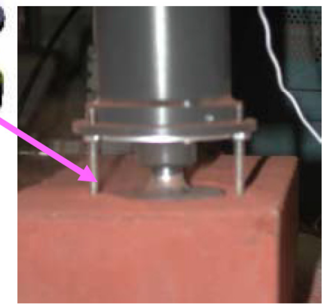
Differential response in the range of 545nm and 700nm



Ultrasonic Rock Abrasion Tool (URAT)

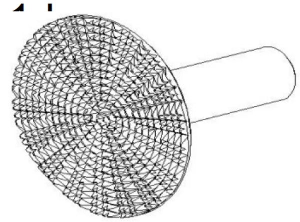


- URAT was developed to the level of proto-flight unit as a backup for the Mars '03 mission
- Several novel mechanisms and designs resulted from this task including
  - The folded horn for shortening the URAT
  - Bit with asymmetric teeth pattern on the cutting edge to induce rotation.
- The URAT mass = 0.400 kg, length = 14.4 cm largest diameter = 6.35 cm and total max volume = 460 cm^3. 20-W power was used to removed 4-cm diameter, 5-mm deep from limestone in 20-min and from basalt



Proto-flight unit

Folded horn

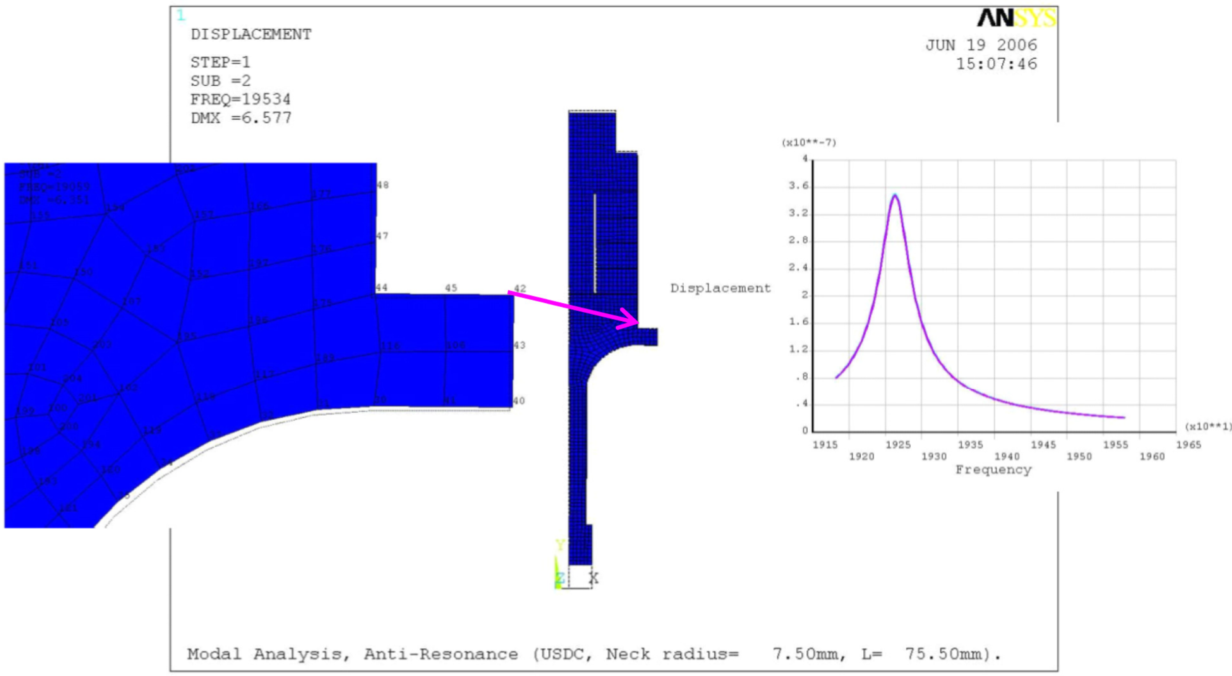


URAT bit with asymmetric teeth pattern

Abraded basalt

Drive electronics

Hammer-Rotary using two independent actuators



- Added bit rotation and external flutes for cuttings removal
- Electrical motor running at low power/ RPM to rotate the bit using a through shaft

High Temperature Piezoelectric Actuated Sampler for Operation on Venus

Percussive Augmenter of Rotary Drills

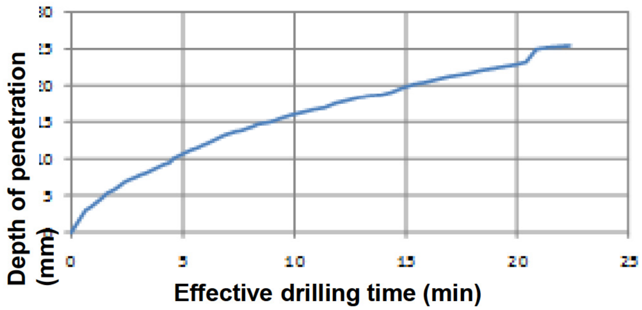
Objective

Strategic objectives

- Establish sampling capability for missions to Venus
- Advance the development of samplers for planetary bodies with higher temperatures.

Technical objectives

- Develop a sampler breadboard that can be operated at temperatures as high as 500°C
  - Develop new piezoelectric ceramic actuator with high electromechanical conversion efficiency at 500°C.
  - Produce ultrasonic/sonic driller and corer (USDC)-based sampler for cores and powdered cuttings



Accomplishment:

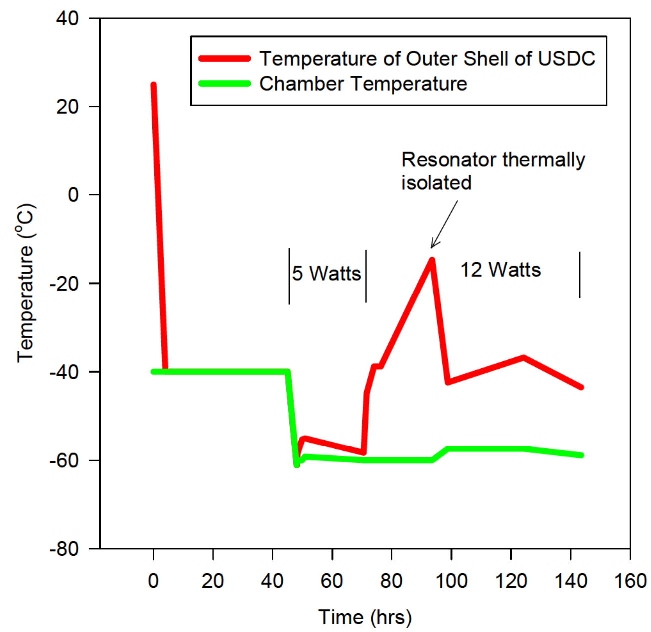
1. Developed novel design that makes the drill a rotary-hammer - the rotation is generated by the vibration of the piezoelectric actuator.
2. Isothermal tests of $LiNbO_3$ piezoelectric discs at 500°C for 1000 hours yielded no change in properties
3. Novel horn and free-mass designs increased the coupling and maintain pre-stress and thermal stability and also induced rotation.
4. Bismuth Titanate with various doping of tungsten showed thickness coupling coefficient that is about 15 to 20% at 500°C.
5. Successfully drilled at 460°C thru a 25 mm thick brick sample in 21 minutes accumulated time. This is a significant accomplishment for this very challenging task and it required a lot of innovation to reach this success [submitted several related New Technology Reports]. The use of brick sample was chosen since more uniform properties were observed as opposed to natural rocks.

USDC at Low temperatures

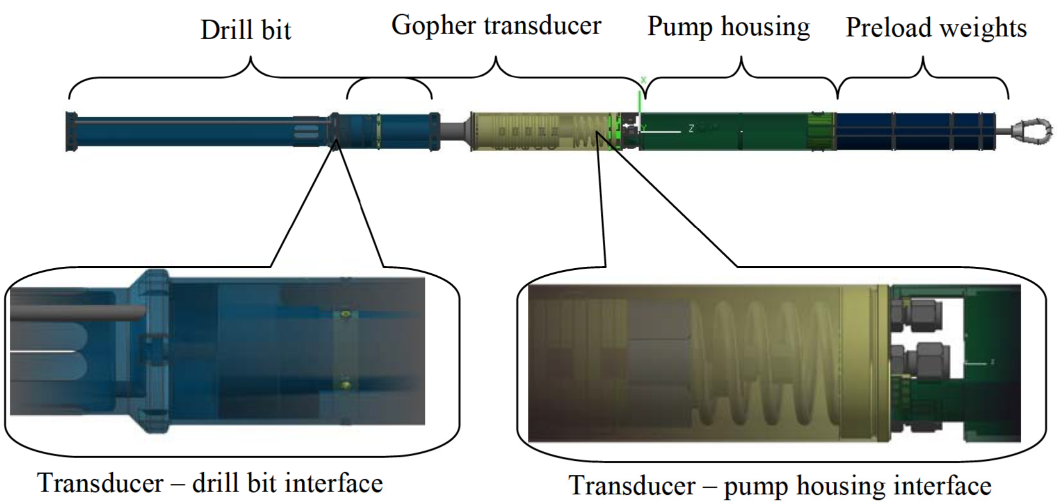
Demonstrated drilling cold ice including: -40°C crashed ice, crashed ice with water and solid ice as well as -140°C in crashed ice and solid ice.

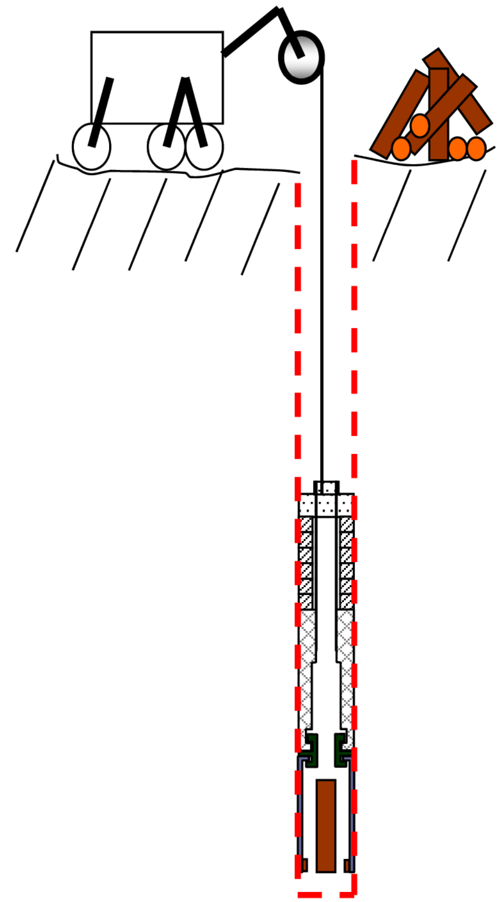
- **Crashed ice at -40°C and 140°C -** At both -40°C and 140°C no problem drilling and the speed was too fast to measure.
- **-40°C slush ice with water** - Drilled 7mm deep using 6-mm diameter drill in 1-minute.
- **-40°C solid ice -** About 1-cm in about 30-sec.
- **-140°C solid ice -** Cored about 3-mm deep using a 10-mm diameter
- **-40°C and -60°C** - Environmental testing for 160 hours

Tests were done at the JPL's Extraterrestrial Materials Simulation Laboratory.



Gopher – tested at Mt. Hood





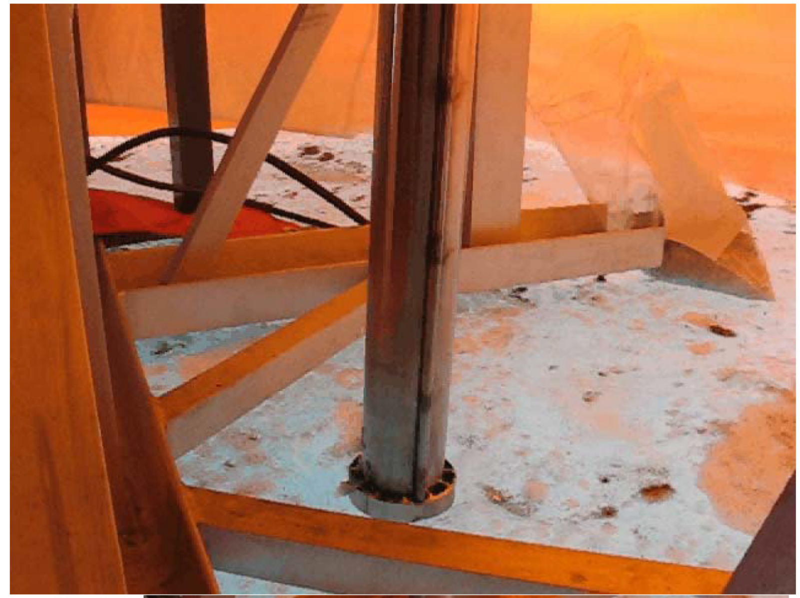
Mt. Hood test site

Close up view of the drill site

Field test in Lake Vida, Antarctica

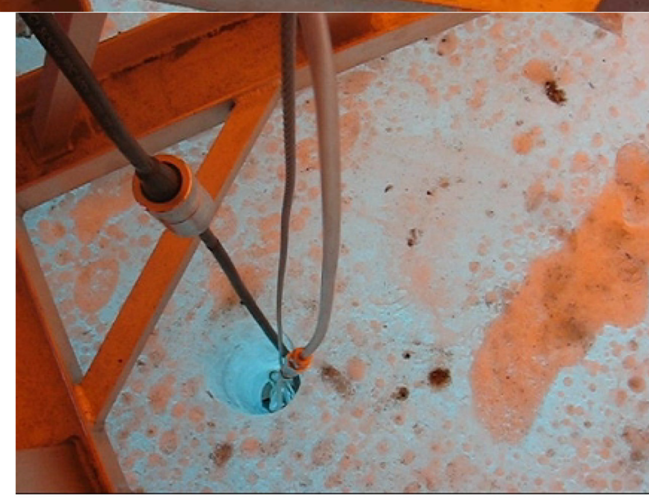
A total depth of 176cm was reached

The Lake Vida test site



Inside the drilling tent

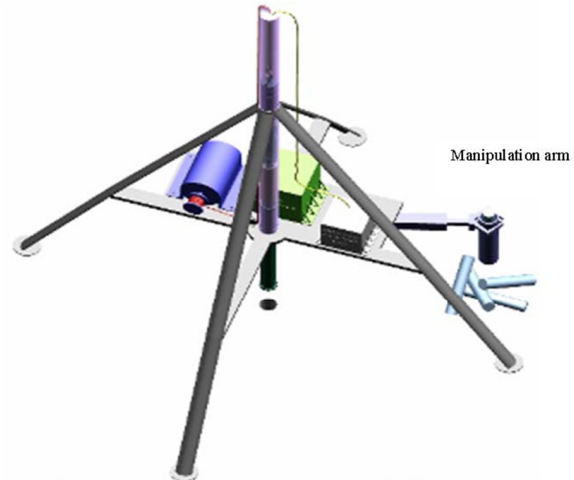
The gopher in the drilled hole

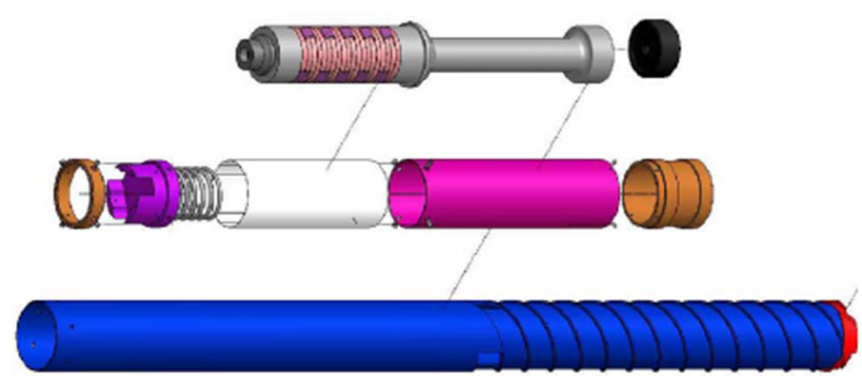


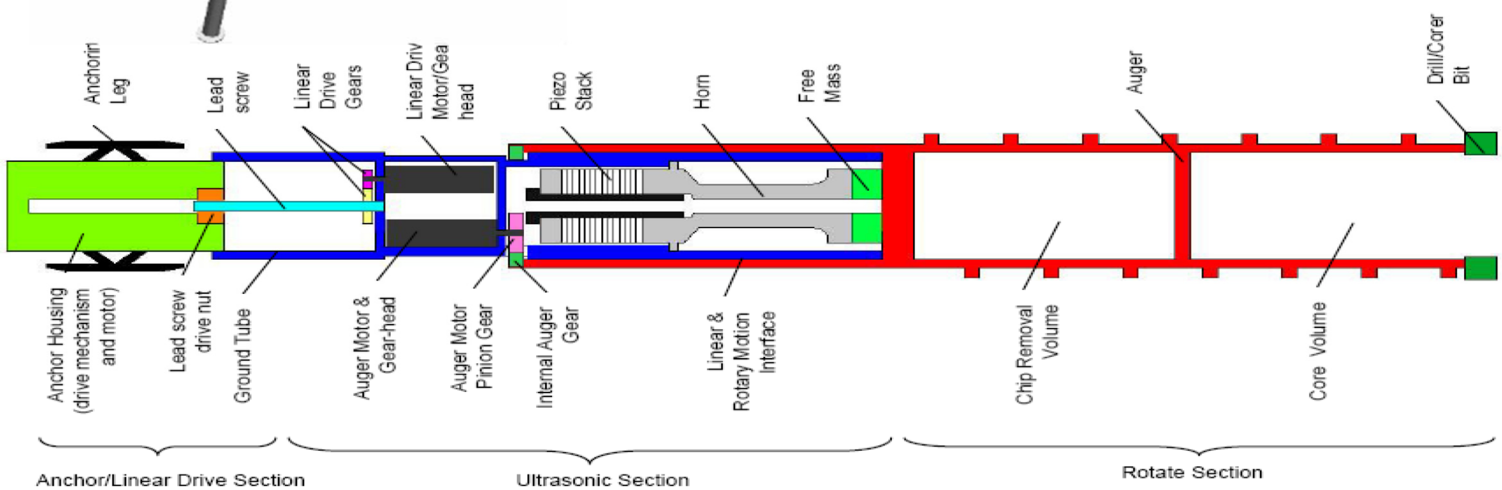
Auto-Gopher for deep drilling

Developing the Auto-Gopher with Honeybee Robotics under an ASTEP task.

The device will be demonstrated to drill about 3 to 5 meters deep in gypsum.

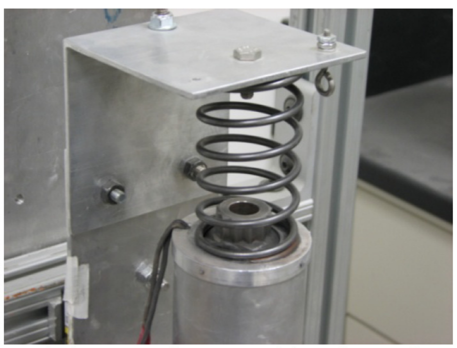


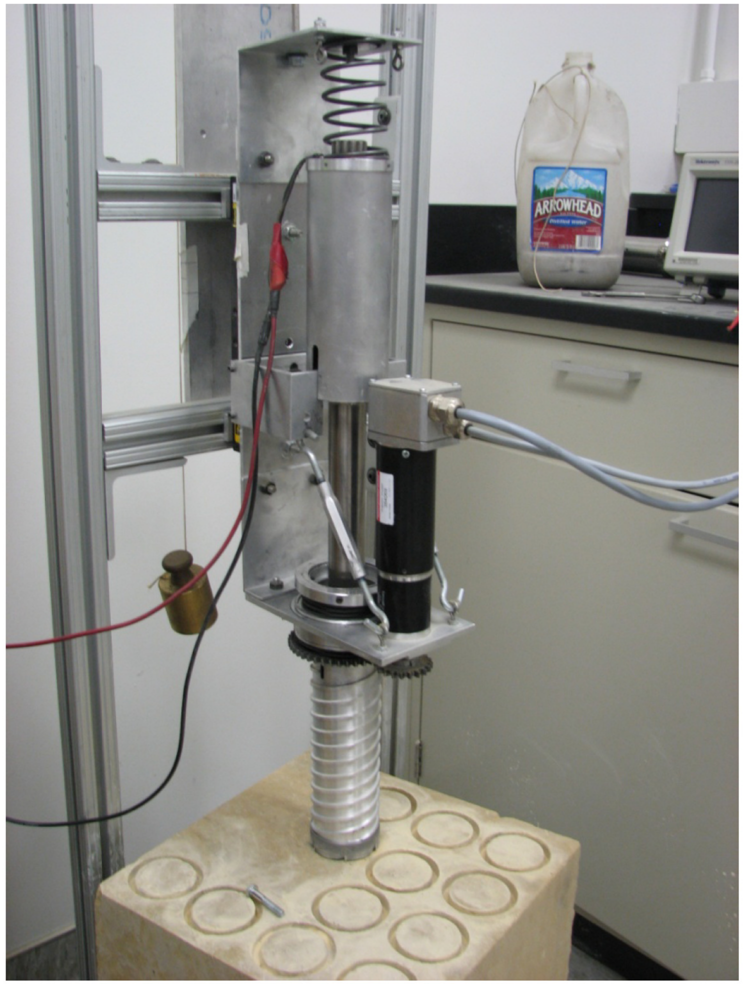




The Auto-Gopher lab-version

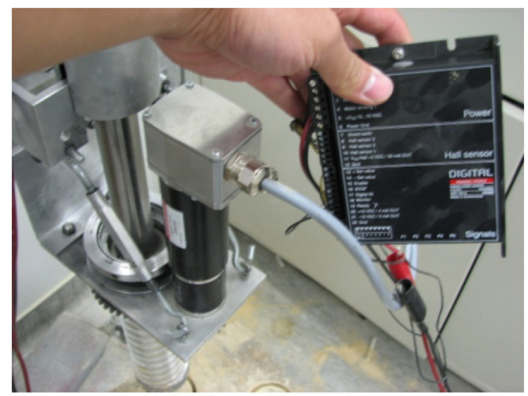

Rotary Drive System


Transducer Preload



Auto-Gopher and Testing Setup

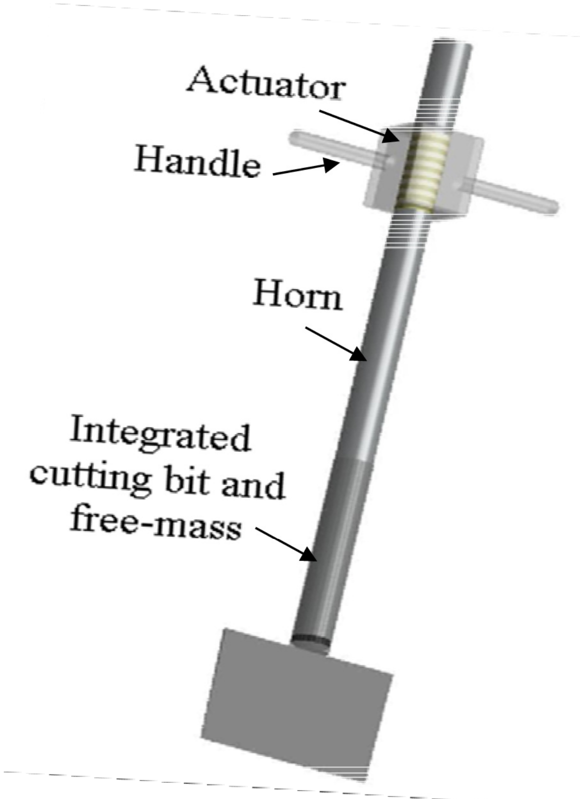

Crown Ring



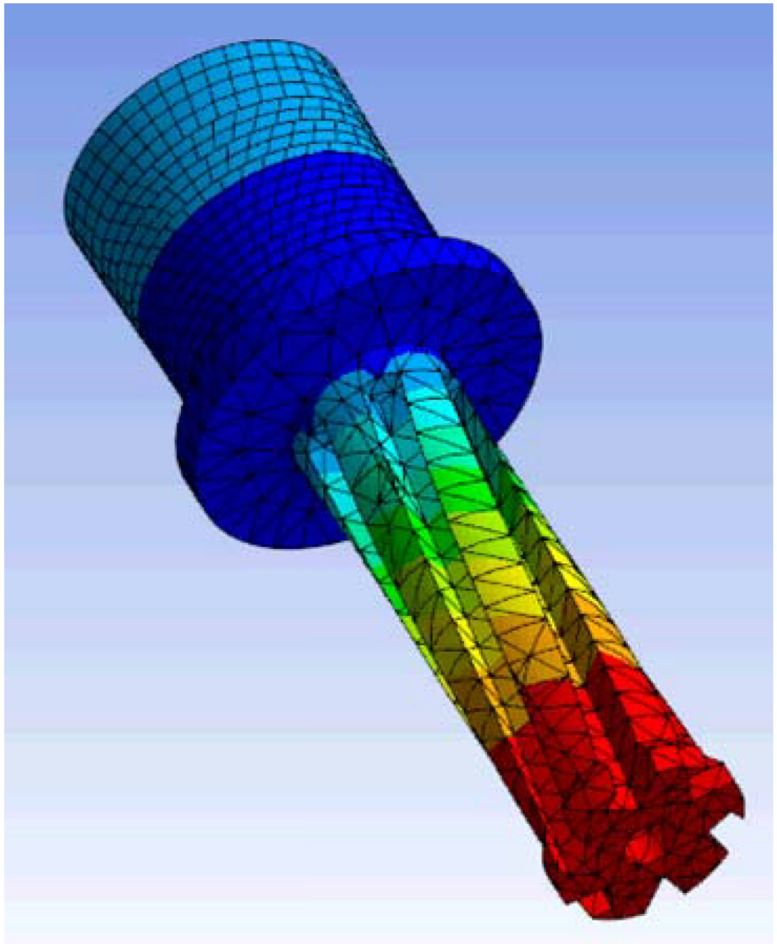
Motor Control

Piezoelectric actuated Jackhammer

Jackhammer system is driven by an ultrasonic/sonic actuator and it chisels rocks, concrete, hard asphalt and other brittle materials and structures without causing damage to plumbing, wiring, metal rebar and other ductile imbedded fixtures.



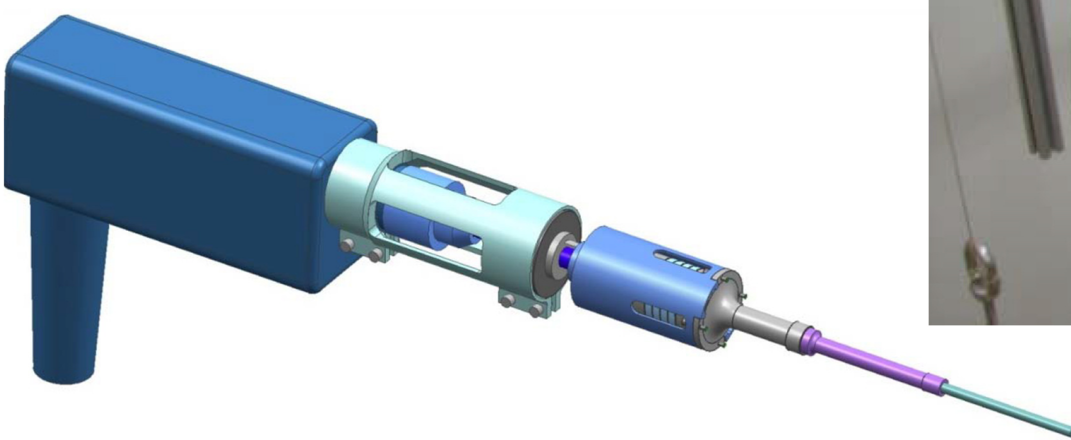
Rotary Hammer Drill using a single Piezoelectric Actuator



The Augmenter development

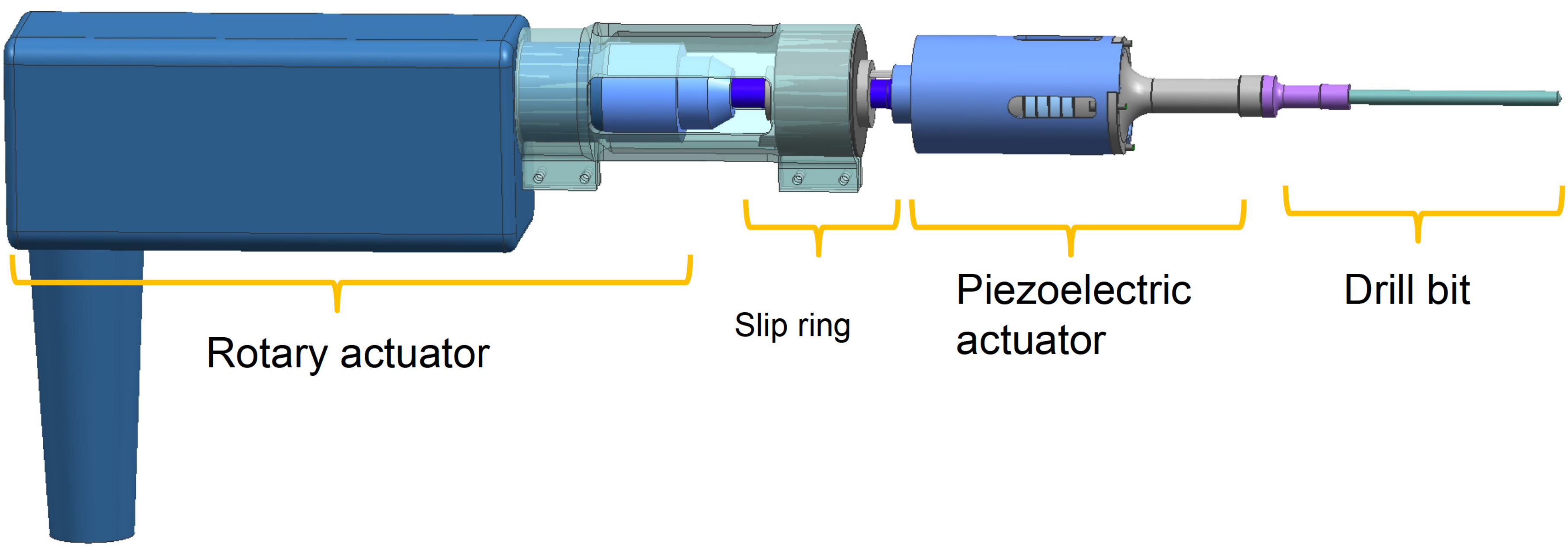
A scaled down version of the PARoD was designed, analyzed and built. The components are:

- A scaled-down ultrasonic actuator.
- A commercial ¼” drill bit
- A rotary drill



The PARoD design for 0.25” bit subsystems

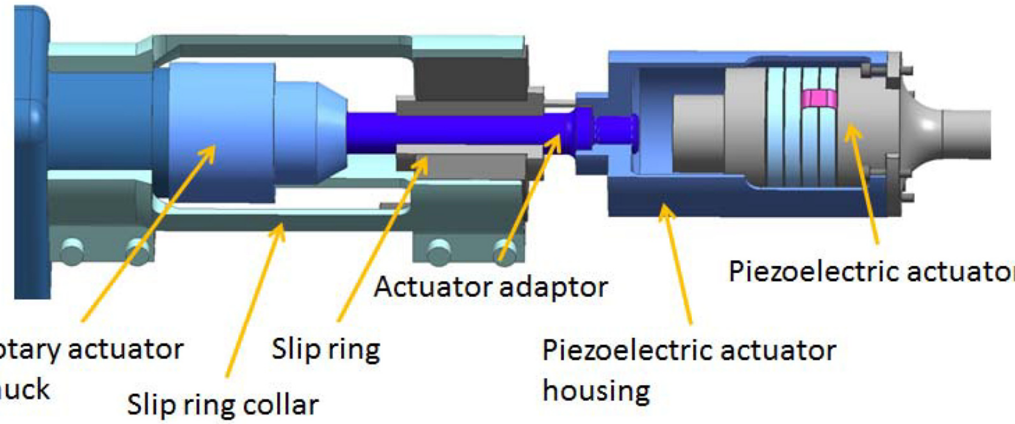
- Three main subsystems:
  - Drill bit
  - Piezoelectric actuator
  - Rotary actuator
- Interfaces:
  - Drill bit adaptor
  - Ultrasonic actuator adaptor with slip ring



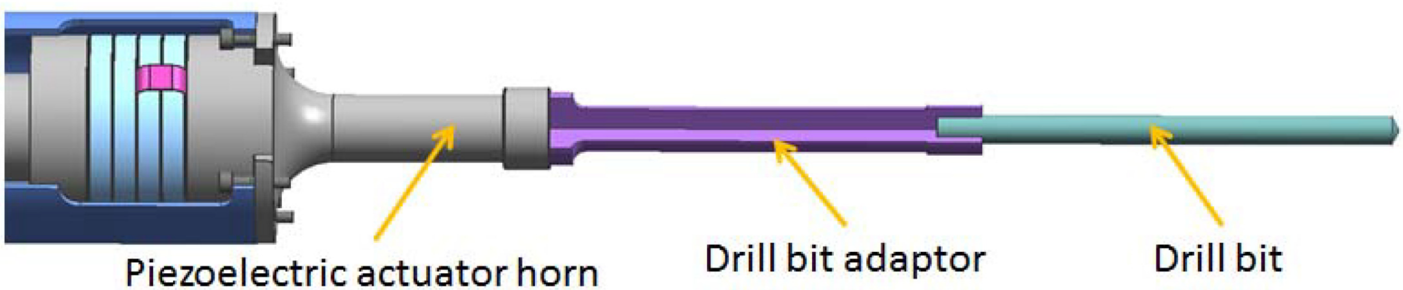
The Percussive Augmenter of Rotary Drills

The PARoD design with 0.25" diam. bit

- The piezoelectric actuator provides ultrasonic axial vibrations to the drill bit
- It is attaches to the rotary actuator thru a housing and an adaptor
- It is powered using a slip ring

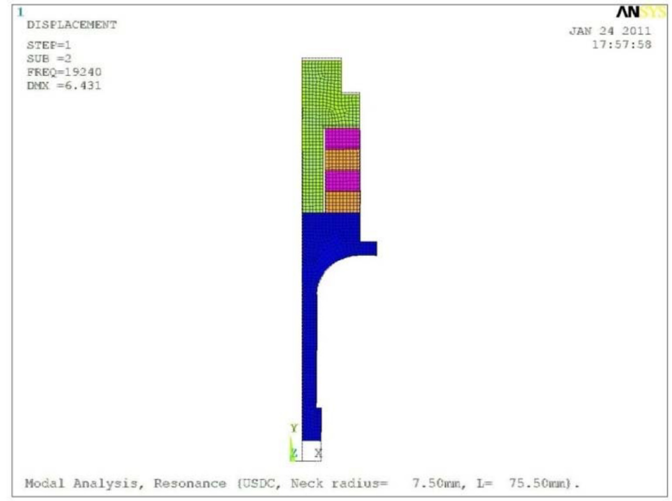


- Commercial ¼" masonry drill bit
- The drill bit was brazed into the adaptor
- The drill bit adaptor was bolted into the piezoelectric actuator horn
- The drill bit adaptor length was determined from analytical modeling

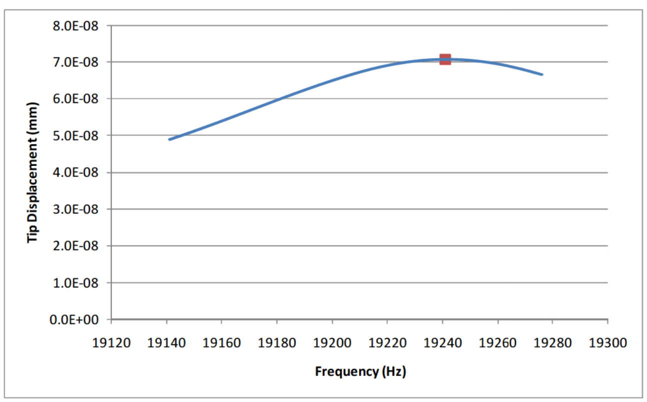


Analysis of the ultrasonic actuator

- The actuator is axisymmetric, and ANSYS axisymmetric elements were used to construct the model.
- Modal analysis was performed. The resonance frequency was predicted at 19240 Hz, and the electro-mechanical coupling factor is 0.17.
- Harmonic analysis was performed. The figures below show the horn tip displacement and the power consumption.

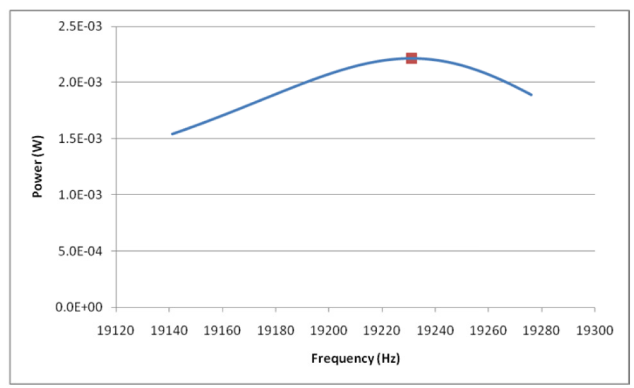


19241 Hz, Tip Disp: 0.0707 µm, for 1 volt input



Horn tip displacement VS. Frequency

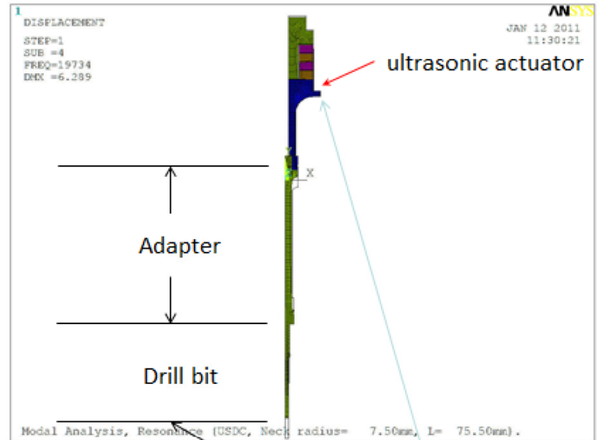
19231 Hz, Power: 0.00222 W, for 1 volt input



Power VS. Frequency

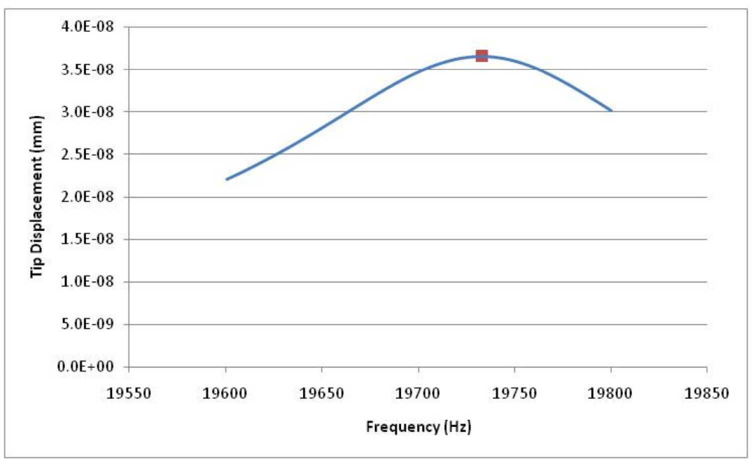
Analysis of the PARoD

- Modal analysis was performed. The Resonance frequency was predicted at 19734 Hz, and the electro-mechanical coupling factor is 0.09.
- Harmonic analysis was performed. The figures below show the drill bit tip displacement and the power consumption.
- Length of the adapter is 80 mm.



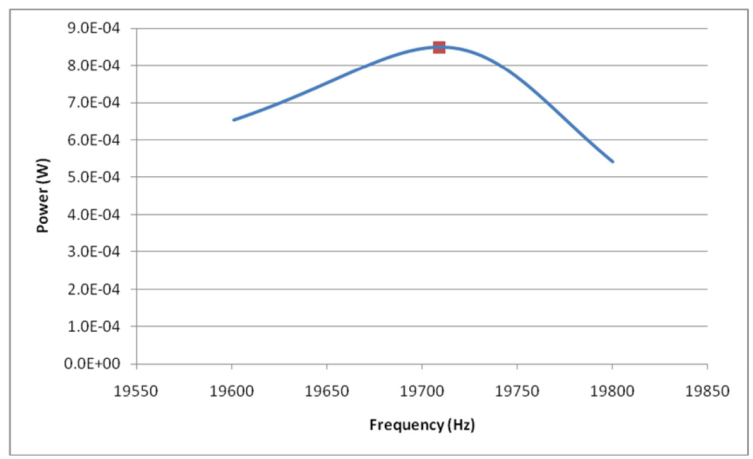
Boundary condition: Edges of the ring fixed

19734 Hz, Tip Disp: 0.0366 μm, for 1 volt input



Horn tip displacement VS. Frequency

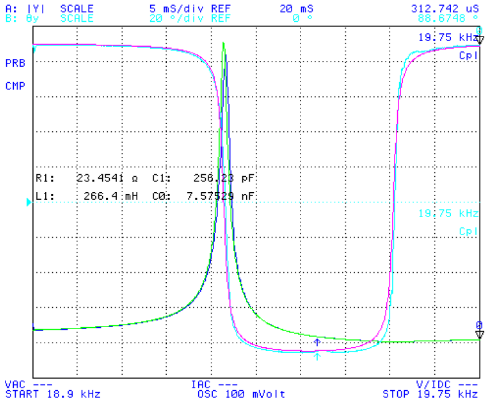
19709 Hz, Power: 0.00085 W, for 1 volt input



Power VS. Frequency

Analysis of the PARoD (continue)

- The PARoD with various size adapters were analyzed.
- The table below shows the comparison of the results for different size adaptors.
- The mode shape shown on the right is for 10 mm long adapter.



The equivalent circuit parameters				
R1	23.45		fp	1.9587E+04
L1	0.27		fs	1.9264E+04
C1	2.56E-10		Q	1375
C0	7.58E-09		k	0.20
			keff	0.18

Adapter Size				100 Volt Input	
Diameter (mm)	Length (mm)	Frequency (Hz)	Coupling Factor	Tip Disp (μm)	Power (Watt)
5.0	10.0	30466	0.33	6.65	169
5.0	30.0	27020	0.15	5.26	34.4
5.0	50.0	23214	0.11	3.72	13.9
5.0	70.0	20674	0.10	3.59	9.6
5.0	80.0	19734	0.09	3.66	8.5

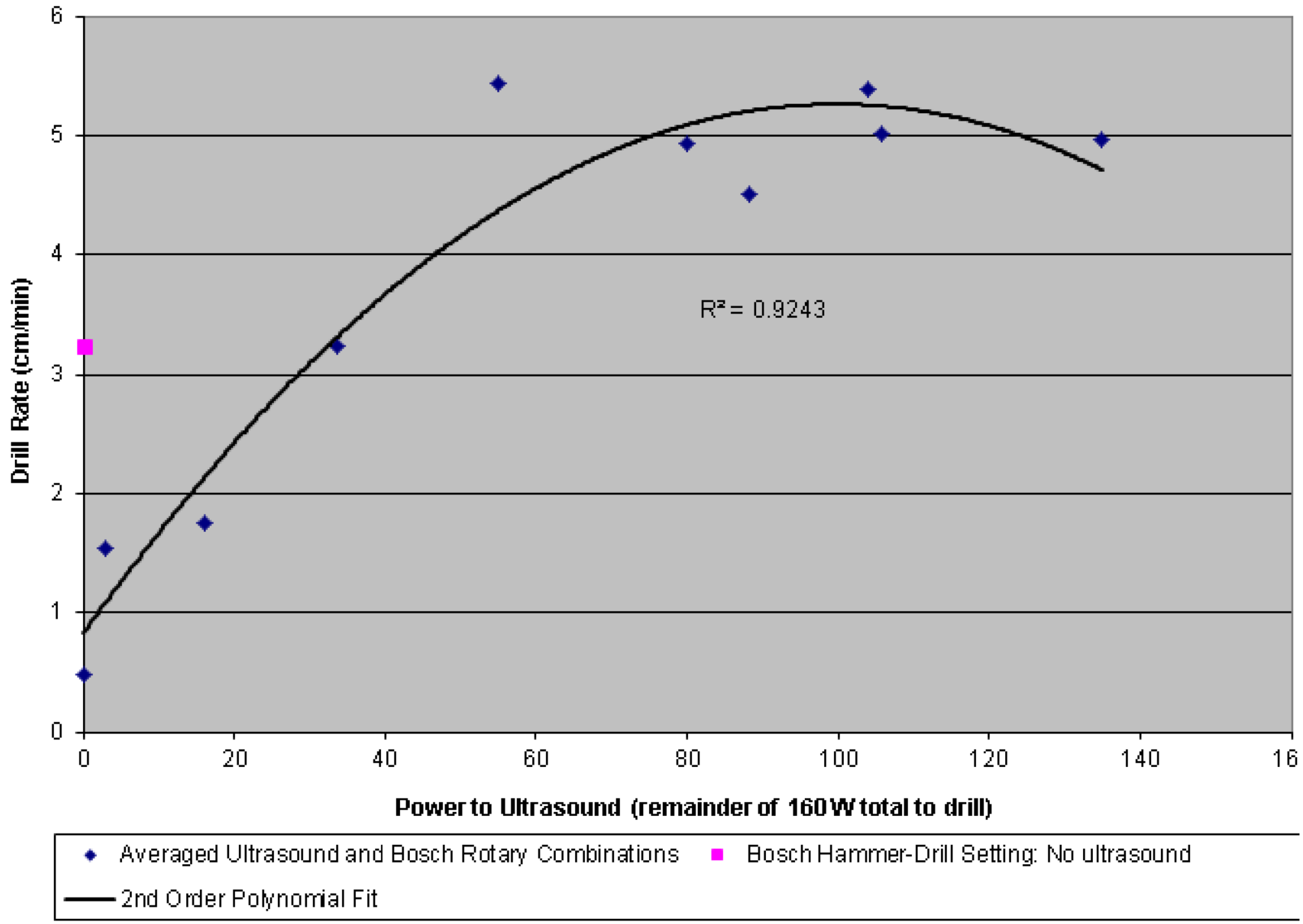
Tests of the PARoD with 0.25” diam. bit

At constant 160W rotary-hammering

Bosch				Ultrasound										
Power	Voltage	Current	Rotation	V amplifier	Power	Highest Power*	Volt age	Current	Frequen cy	Depth	Time	Rate	Total Power	Total Max Power
Watts	V	Amp	RPM	V	Watts	Watts	V	Amp	KHz	cm	min	cm/min	Watts	Watts
162	69	2.31	800	0	0	0	0	0	0	0.9	2.1	**0.43**	162	162
158	70	2.28	770	0.1	2	4	65	0.14	22.7	2.4	1.5	**1.60**	160	162
129	63	2.21	695	0.2	16	21	110	0.25	22.5	3.2	1.2	**2.67**	145	150
120	61	2.03	675	0.3	26	35	150	0.4	22.4	3.2	0.6	**5.33**	146	155
105	57	1.94	640	0.4	48	55	170	0.52	22.3	3.6	0.8	**4.50**	153	160
													0	0
103	58	1.95	636	0.6	70	80	250	0.62	22.2	3.1	0.7	**4.43**	173	183
85	54	1.8	590	0.6	80	90	230	0.7	22.2	4.3	0.6	**7.17**	165	175
74	50	1.73	547	0.6	75	85	240	0.7	22.2	3.2	1.25	**2.56**	149	159
71	47	1.68	528	0.7	90	100	265	0.78	22.1	3	0.72	**4.17**	161	171
71				0.7	85	90	270	0.7	22.2	3.2	0.72	**4.44**	156	161

Tests of the PARoD with 0.25” diam. bit

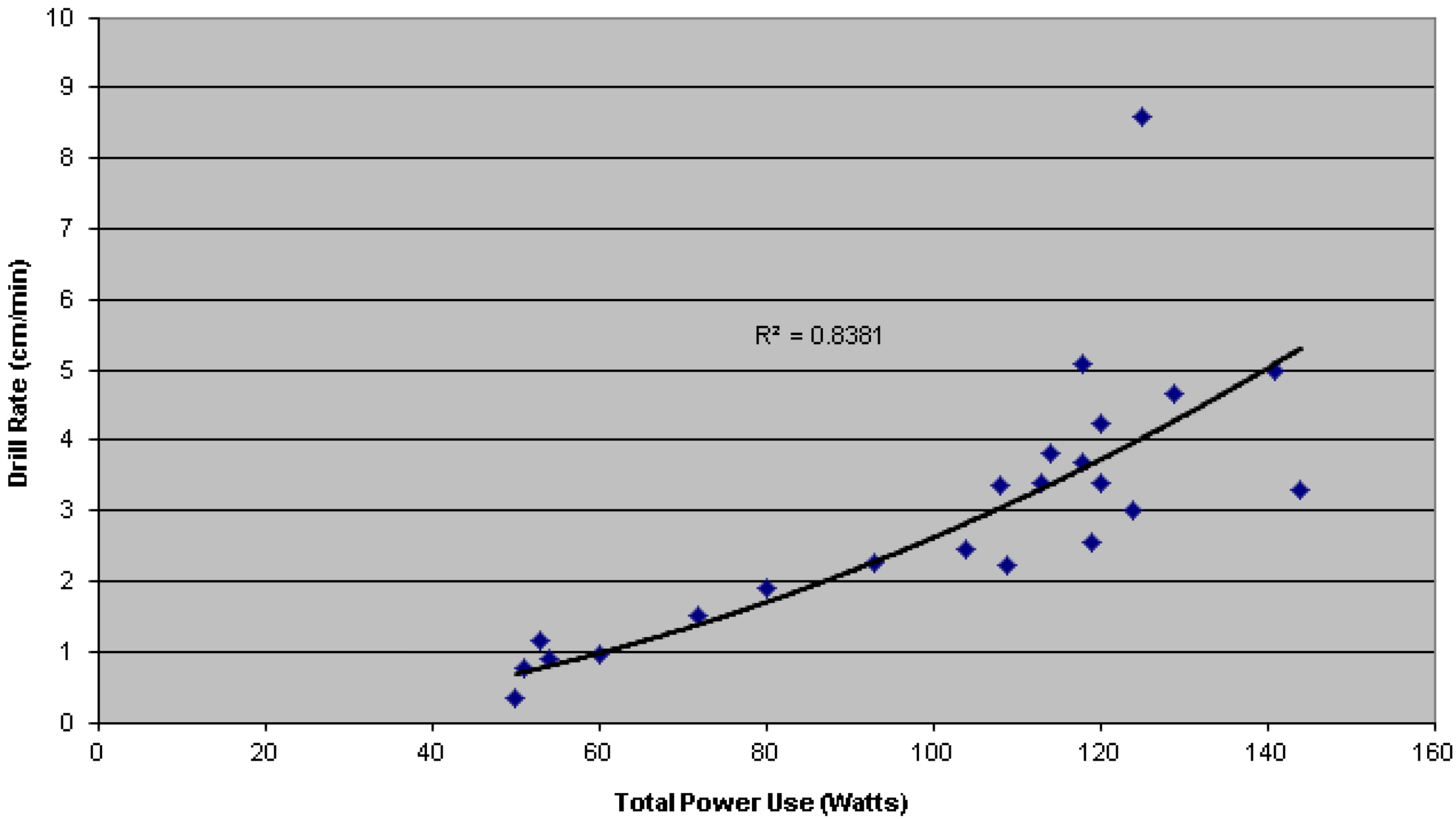
Combining rotation and hammering



Averaged Drill Rates in **Limestone** at Constant Total Power 160 Watts with 4.2 kgf Load

Tests of the PARoD with 0.25” diam. bit

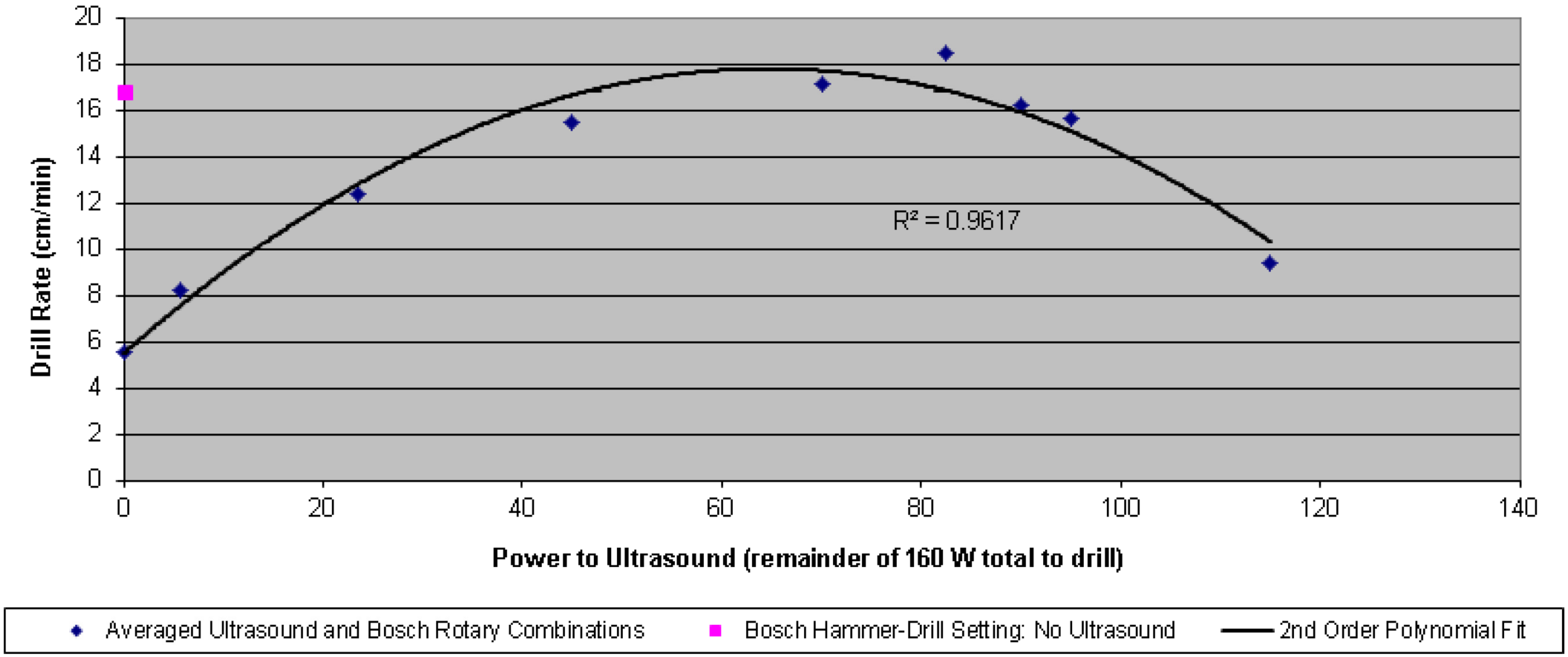
Fixed power to rotation and increased power to hammering



Drill Rates in Limestone vs. Total Power Used, Rotary Power of ~50 Watts and 4.2 kgf Load

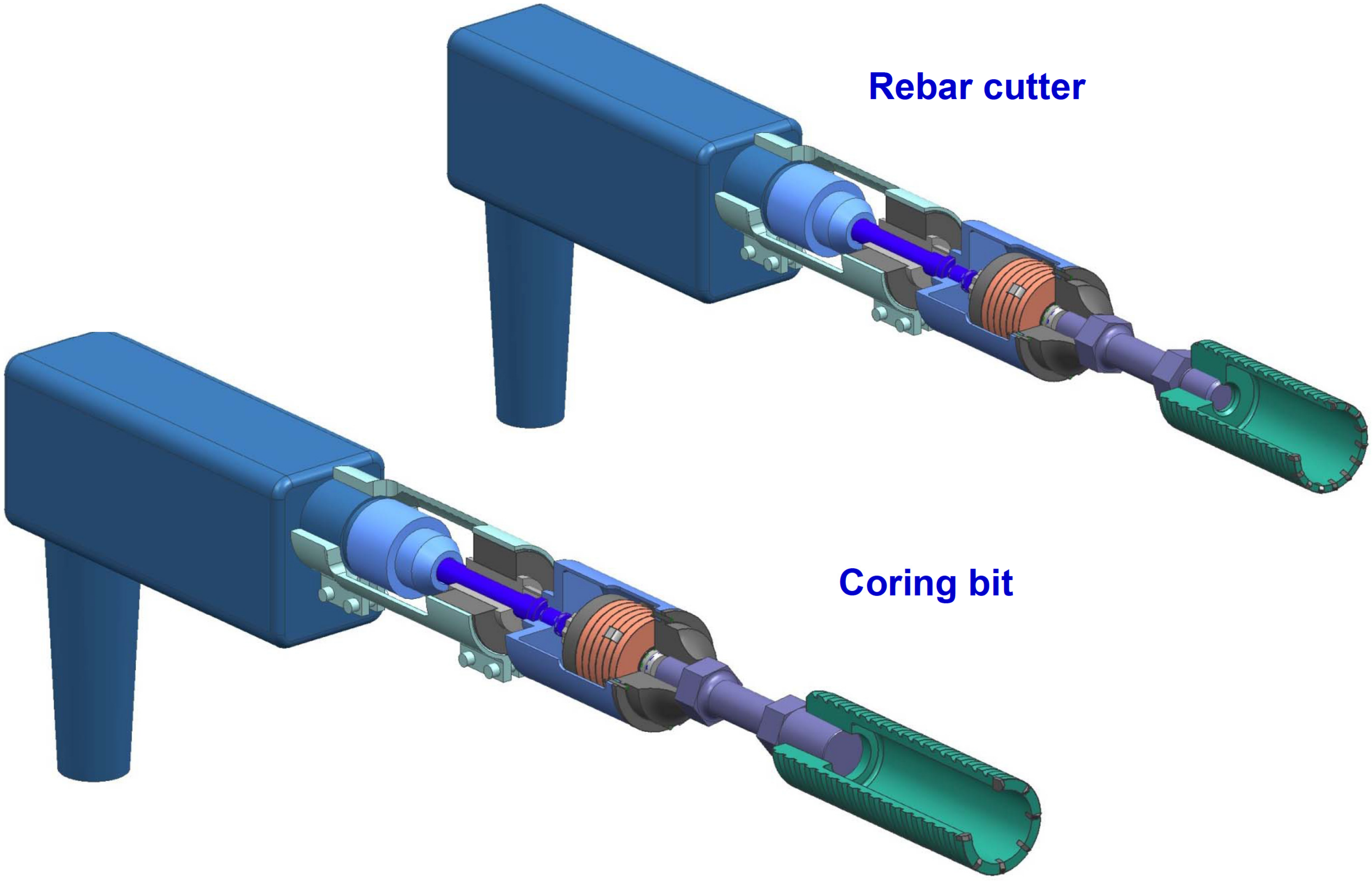
Tests of the PARoD with 0.25" diam. bit

Combining rotation and hammering

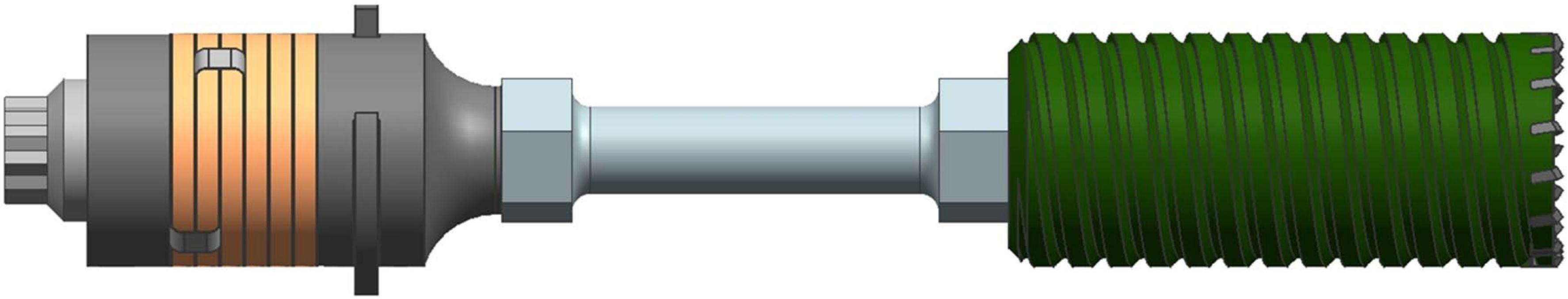


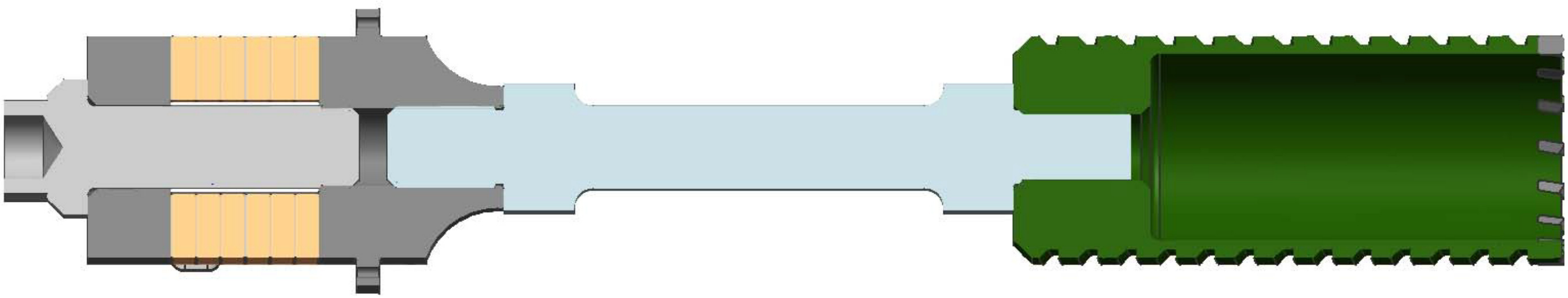
Averaged Drill Rates in Concrete at Constant Power 160 Watts and 4.2 kg Load

Integrated augmenter with 2” coring bit, slip ring and rotary drill

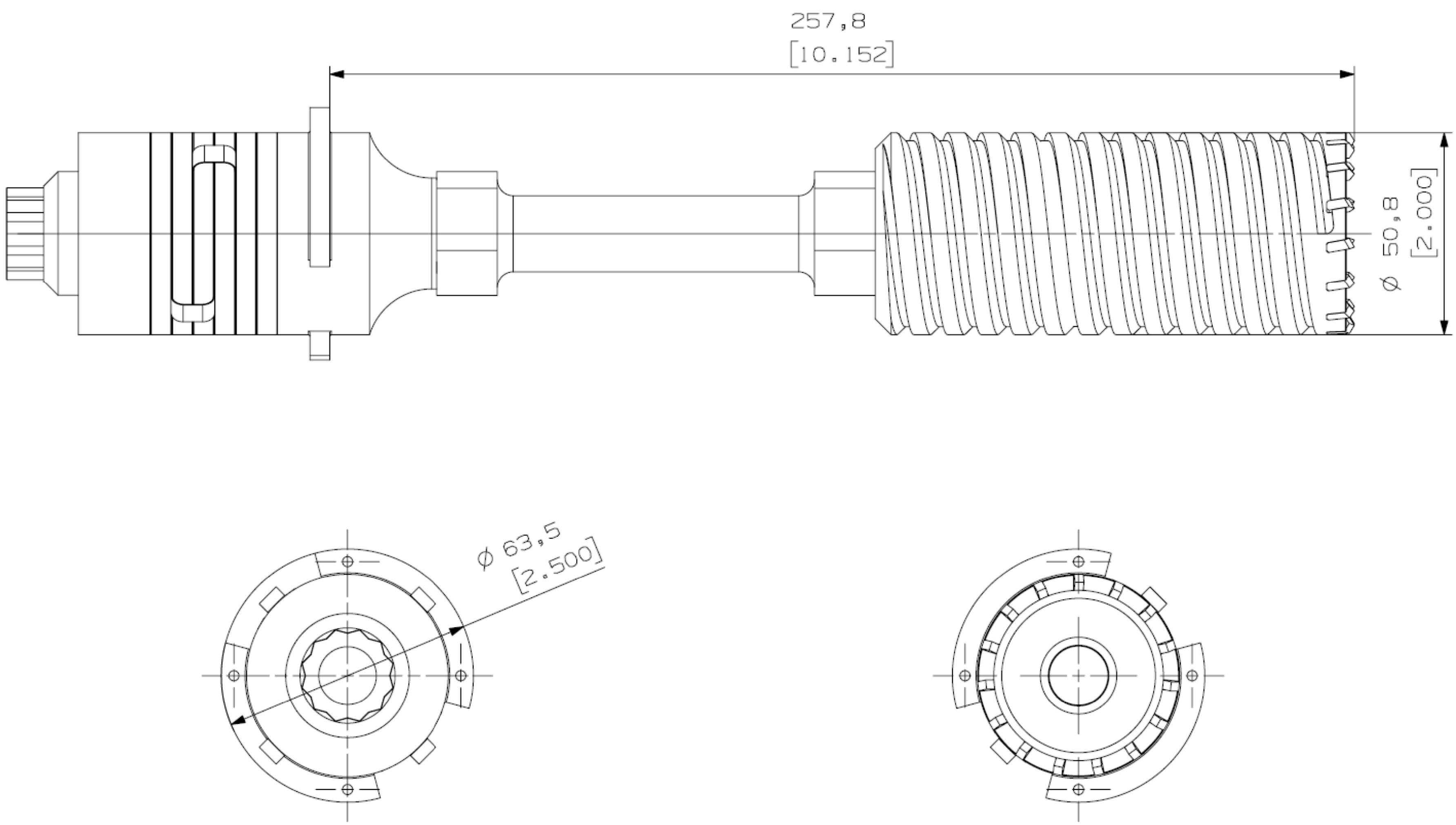


Augmenter with 2” coring bit design

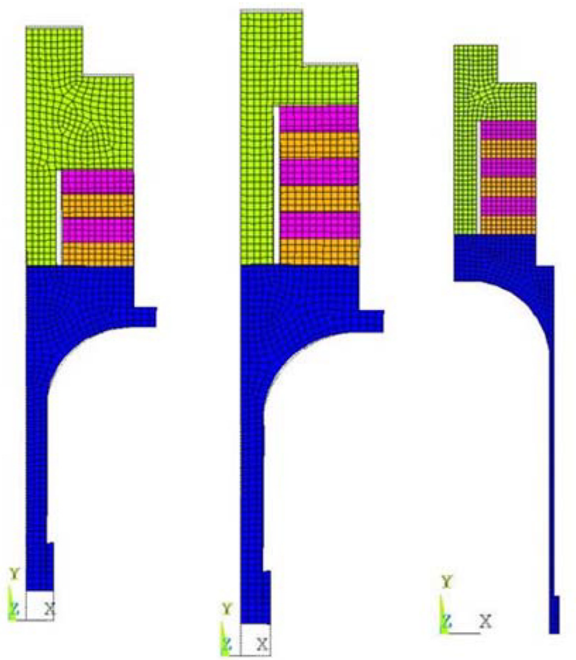




Augmenter with 2” coring bit design

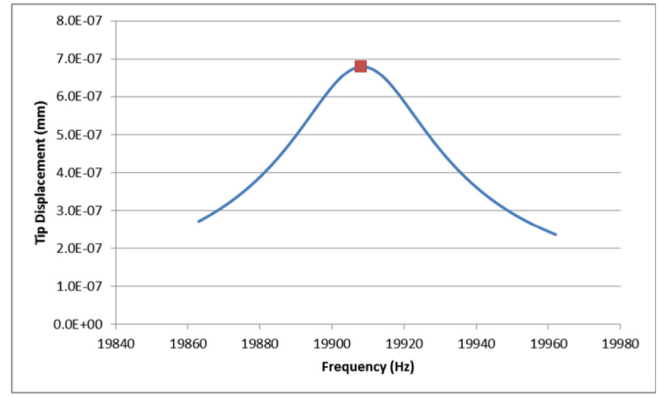


Modeling the PARoD with 2" coring bit



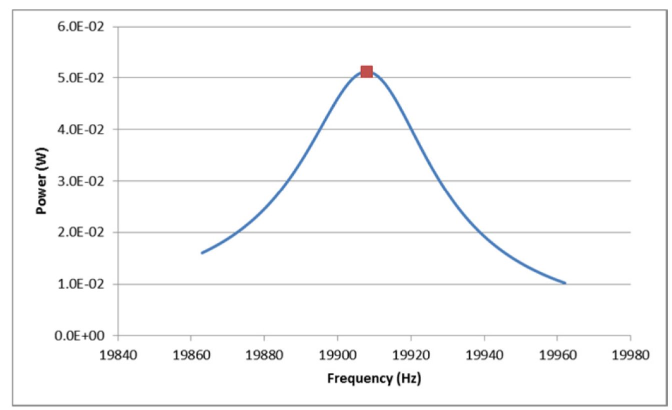
1 stack – 4 PZT   1 stack – 6 PZT   1 stack – 6 PZT, inverted

19908 Hz, Tip Disp: 0.680 µm, for 1 volt



Horn tip displacement VS. Frequency.

19908 Hz, Power: 0.0512W, for 1 volt



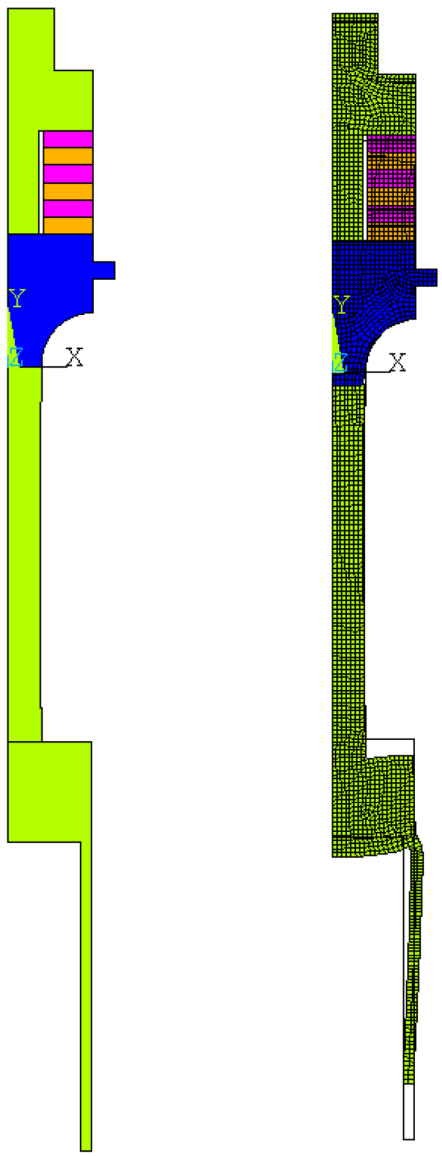
Ultrasonic actuator power consumption VS. Frequency.

Performance of the new designs

Design	Frequency (Hz)	Mechanical Q	Power (Watt)	Tip Disp (µm)	Voltage (V)
1 stack - 4 PZT	20026	500	1.0	3.269	6.175
3 stack - 4 PZT	19912	500	1.0	3.003	4.418
1 stack - 6 PZT	19966	500	1.0	3.237	4.436
1 stack - 6 PZT, inverted	11969	500	1.0	4.601	10.602

Modal analysis of the PARoD with 2" coring bit

Examining the location of the nodal plan



PARoD with 2" coring bit

Summary

- Numerous designs were made following the development of the USDC and analytical modeling of its configuration.
- A prototype PARoD with 0.25” bit was produced.
  - Finite Element Analysis of the actuator has been performed.
  - Assembled PARoD with various size of adaptors has been analyzed.
  - The resonance frequencies, drill tip displacement, and power consumption have been predicted.
- Tests have shown as much as 10 times increase in drilling rate using a fix total power of 160 Watts compared to drilling with rotary only
- Compared to a commercial rotary hammer at 160 Watts and 4.2 kg preload the augmenter showed ~1.7x increase in drilling rate
- An augmenter with 2” coring bit design was developed and its configurations is currently being optimized.